Assessing the sound insulation and thermal performance of a partition based on recycled materials as a sustainable retrofitting solution for buildings

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Abstract. Global warming and carbon emissions force us to rethink the use of our resources in a circular way. Recycling of materials such as paper and bio-based products offers an economically viable and straightforward way to reuse waste products. In this paper, a lightweight partition based on cellulose and agro-industrial byproducts is evaluated in terms of their sound insulation and thermal performance. Various combinations were assessed using a vibro-acoustic method suited for beam samples, with bending stiffness determined from normal modes and sound transmission loss derived accordingly. Additionally, the acoustic transfer matrix elements were characterised based on the measurements, facilitating the subsequent design of multilayer partitions using inverse procedures. The thermal aspect was studied measuring the thermal conductivity of the samples. Comparative analyses with analytical models and prior literature were conducted to validate the findings. Sandwich partition exhibited the higher sound insulation performance and potentially greater thermal insulation compared to the homogenous material. Applications are oriented to develop sustainable partitions for the retrofitting of buildings.

1 Introduction

In recent years, the necessity to discover alternative and sustainable materials has become increasingly critical for mitigating carbon emissions and lessening environmental impact across various sectors, including green buildings. It is crucial not only to manage the energy consumption within the building but also to ensure that the materials used for the retrofitting are environmentally friendly.

Numerous studies demonstrate the viability of utilizing resources from waste and circularly creating new components. In this way, paper and cardboard stand out as some of the most abundant materials that can be easily recycled. In [1] the acoustic and thermal performance of cardboard-based panels from the packaging industry are evaluated, showing good sound insulating properties and acceptable thermal conductivity in comparison with standard insulators. In other studies, the focus is put on optimizing the microstructure of natural hemp [2] and basalt fibres [3] to improve their thermal and acoustic insulation performance. Sandwich partitions are often preferred due to the high stiffness-to-weight ratio allowing high insulating properties with less thickness compared to homogeneous structures. Bio-based materials such as cork, pine wood and balsa can be used as cores, and cotton, bamboo and carbon fibre for the face sheets [4].

In this paper, the acoustic and thermal insulating properties of paper-based panels combined with an agro-industrial residues are evaluated by applying a vibration test on beam samples and thermal conductivity measurements on small scale samples respectively.

2 Theoretical background

2.1. Vibrational modes of a beam

The bending modes of sandwich structures have been discussed in previous studies [5][6]. According to Nilsson [5] the apparent bending stiffness D_x of an infinite panel can be derived from the flexural vibrations of a beam sample both for homogeneous and sandwich structures. In the last case the core is assumed to be rigid enough to ensure the laminates are moving in phase. For a beam with free suspended boundary conditions having a length L and mass per unit area μ, the apparent bending stiffness for the f_n eigenfrequency is defined as:

$$D_{x,n} = \frac{4\pi f_n^2 \mu L^4}{\alpha_n^4} \tag{1}$$

where $\alpha = n\pi + \pi/2$, for $n = \{1, 2, 3, 4 \ldots\}$. For a homogeneous panel D_x is constant with frequency, but for sandwich panels it is frequency dependent. By fitting the measured data at specific eigenfrequencies, the bending stiffness can be defined in all the frequency range of interest. The Young modulus of the material can be derived from the bending stiffness and the momentum of inertia I of the beam as $E = D/I = 12D/bh^3$, with b the height and h the thickness of the beam.

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The coincidence frequency f_c occurs when the wavelength of a flexural wave on the wall coincides with the wavelength of the waves in the surrounding air and it can be calculated as:

$$f_c = \frac{c^2}{2\pi}\sqrt{\frac{\mu}{D}} \tag{2}$$

where c is the speed of sound in air and D can be replaced by the apparent bending stiffness of the plate D_x when frequency dependent. This implies that for a single wall f_c is constant but for a sandwich panel is frequency dependent.

The sound transmission loss (TL) in dB for an infinite panel is defined as [6], $TL = -10log(\tau_d)$, where τ_d is the sound transmission coefficient for diffuse field incidence given by:

$$\tau_d = 2\int_0^{\pi/2} \tau(\theta)\cos(\theta)\sin(\theta)\,d\theta \tag{3}$$

The transmission coefficient as a function of the angular frequency ω and angle of incidence θ is:

$$\tau(\omega,\theta) = \left\{\left[1 + \frac{\mu\omega}{2\rho c}cos(\theta)\left(\frac{f}{f_c}\right)^2 sin^2(\theta\eta)\right]^2 + \cdots \left[\frac{\mu\omega}{2\rho c}cos(\theta)\left(\left(\frac{f}{f_c}\right)^2 sin^2(\theta) - 1\right)\right]^2\right\}^{-1} \tag{4}$$

Finally, the acoustic impedance of a single infinite wall can be estimated as:

$$Z_p = -j\omega\mu\left[1 - \left(\frac{f}{f_c}\right)^2 (1 - j\eta)sin^4(\theta)\right] \tag{5}$$

2.2 Transfer matrix method

The transfer matrix method (TMM) provides a relationship between the sound pressure (p) and particle velocity (v) at one side ($x=0$) and the other side ($x=d$) of a specimen, where d is the thickness of the wall. Under the assumption of 1D plane waves and for normal incidence. the general formulation for a rigid multilayer partition for is given by [7]:

$$\begin{bmatrix}p\\v\end{bmatrix}_{x=0} = \prod_{i=1}^{N}\begin{bmatrix}1 & Z_{pi}\\0 & 1\end{bmatrix}\begin{bmatrix}p\\v\end{bmatrix}_{x=d} = T_M\begin{bmatrix}p\\v\end{bmatrix}_{x=d} = \begin{bmatrix}T_{11} & T_{12}\\T_{21} & T_{22}\end{bmatrix}\begin{bmatrix}p\\v\end{bmatrix}_{x=d} \tag{6}$$

where Z_{p_i} is the impedance of the i-th layer defined by Eq. (5). The total transfer matrix T_M is the product of the different transfer matrices T_i for each layer, and the sound transmission coefficient can be derived as:

$$\tau = \frac{2e^{ikL}}{T_{11}+\frac{T_{12}}{Z_0}+Z_0T_{21}+T_{22}} \tag{7}$$

2.3 Thermal parameters

The thermal conductivity indicates how well a material can conduct heat, and thus defines its insulation efficacy. It is defined by:

$$\kappa = q''.d/\Delta T \tag{8}$$

where q'' is the heat flux per unit area, d the sample thickness and ΔT the temperature difference between the samples faces.

3 Materials used and description of the experiments

The sound and heat insulation properties of wall partitions were assessed utilising beam samples combining recycled paper and agricultural residues. Three samples with dimensions $760 \times 55 \times 12$ mm (length-height-thickness) were constructed using crumbled paper (PP), paper (PP) + 30wt% of agriculture residue (AR), (named PPAR) and a sandwich composed by two layers (3 mm) of PPAR and pure AR core (6 mm) (see Fig. 1 and Fig. 2). The binder used was water and tapioca starch with a baking process in a proportion 6:1. The agriculture residues (AR) were granulated (1-3 mm) plant leaves (*Ilex Paraguariensis*) used for infusions. The mass per unit area (μ) of the samples is listed in Table 1.

Table 1. Mass per unit area of the samples.

Property	**S. 1 (PP)**	**S. 2 (PPAR)**	**S. 3 (PPAR+AR+PPAR)**
Mass per unit area ($\boldsymbol{\mu}$) [kg/m^2]	2.74	5.31	9.83

3.1 Sound transmission loss

The beam samples were suspended by string to set free-free vibration boundary conditions and the apparent bending stiffnesses were determined from Eq. (1). An accelerometer PCB type 352A24 was attached to one extreme of the beam and connected to a Bruel & Kjaer PULSE multi-channel analyser. An impulse excitation was generated by an impedance hammer PCB type 086C03. The measurement was performed using the hammer as a signal trigger and the transfer function for each sample was recorded with 6400 FFT lines and rectangular window.

3.2 Thermal insulation

The Transient Hot Bridge method (THB) was applied to measure the thermal conductivity [8]. The advantage of this transient, time dependent method is that it allows shorter measurement times and smaller sample sizes than stationary methods. A strip shaped probe is used as a heat source and temperature sensor mounted between two pieces of sample. Three material samples as showed in Fig. 1 were measured, two of them made of bonded PP and PPAR respectively, and the third one made of AR granules, using a specific sensor for characterising powders.

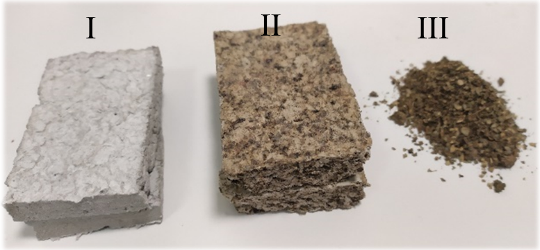

Fig. 1. Materials under test, bonded PP (I), PPAR (II), and AR granules (III).

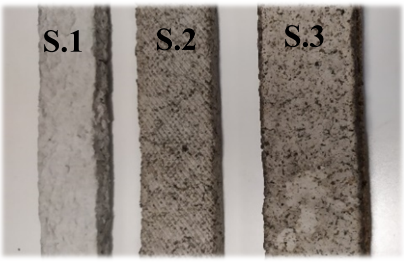

Fig. 2. Beam samples under test.

4 Results and discussion

The elastic modulus was derived from the bending stiffness and the moment of inertia for each beam obtaining values of 189 MPa, 694 MPa for S.1 and S.2, and frequency dependency values from 56 MPa to 265 MPa for S.3. The inclusion of AR granulates to the paper paste conferred more rigidity to the PPAR beam (more than three times the elastic modulus of the PP beam).

A code was written to implement the TMM and derive the sound transmission loss using the transmission index from Eq. (7). The algorithm was validated with a measured TL for diffuse field from previous research [9] and the comparison with literature data is shown in Fig. 3 with good agreement.

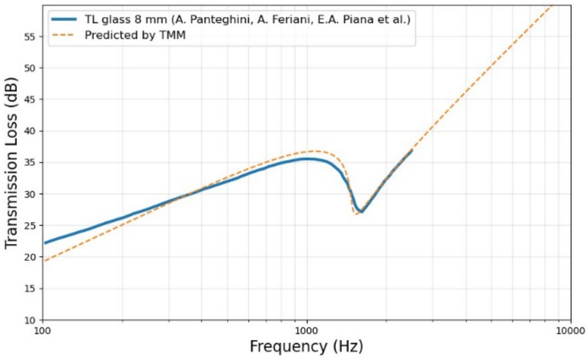

Fig. 3. Validation of the TMM algorithm (dashed) by comparison with measured data (solid) in [9].

The transmission loss for the equivalent infinite panel derived from the beams measurements is shown in Fig. 4, while the mounting setup is shown in Fig. 5. As it can be seen the sandwich sample (S.3) presents the highest transmission loss values as it has the greater mass per unit area. For S.1 and S.2 the curves are separated by 6 dB according to the mass law. Sample S.2 has the lowest coincidence frequency f_c, denoting that the addition the agriculture residue to the paper paste (PPAR) increases the rigidity of the partition.

The sound transmission performance is comparable to that of typical gypsum boards [10] reaching values around 30-40 dB before the resonance frequency.

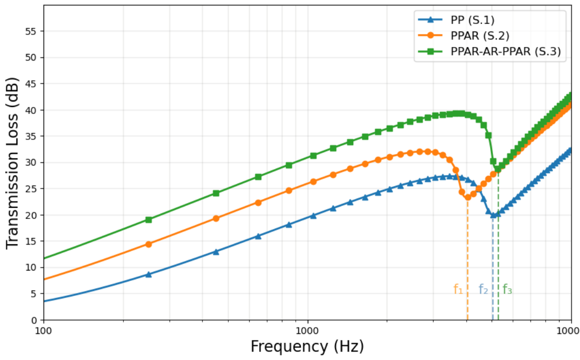

Fig. 4. Transmission loss of the equivalent infinite panels from beam measurements.

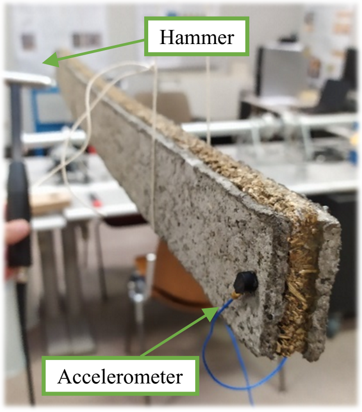

Fig. 5. Suspended beam setup with attached accelerometer.

The thermal conductivities of the samples are listed in Table 2. Samples S.1 and S.2 have similar thermal conductivities values, slightly higher than common insulators as mineral wools (0.04 – 0.06 W/mK). The addition of AR granules (30wt%) in the paper mix seems not to enhance the insulating properties of the material. However, the AR granulates exhibited lower thermal conductivity, comparable to that of insulating materials. Utilizing such a material as the core of a sandwich could potentially enhance the thermal insulation of the partition while also reducing its weight. Additionally, the sandwich offers good sound reduction performance, as depicted in Fig. 4.

Table 2. Thermal conductivity of the sample's materials.

Property	**M. 1 (PP)**	**M. 2 (PPAR)**	**M. 3 (AR)**
Thermal conductivity [W/mK]	0.1112	0.1096	0.0656

5 Conclusions

The acoustic and thermal insulation properties of environmentally friendly and sustainable partitions were evaluated based on measurements taken from beam samples. The calculated values demonstrated effective sound insulation performance, similar to that of typical gypsum boards, indicating a promising alternative for building retrofitting. The sandwich partition exhibited higher sound insulation performance and possibly greater thermal insulation compared to the homogenous material. The bio-based core has shown to be a good insulating material comparable to typical insulators. The evaluation of water and fire resistance was not conducted in this study, nevertheless it remains a crucial point for future investigation.

Future development involves the measurement of the specific heat capacity and the implementation of the TMM for the thermal insulation and to design/optimize the thermal performance of multilayer partitions. Finally, transmission loss measurements of consolidated panels are expected within a transmission room for further validation of the findings.

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